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Jet substructure measurements with ALICE

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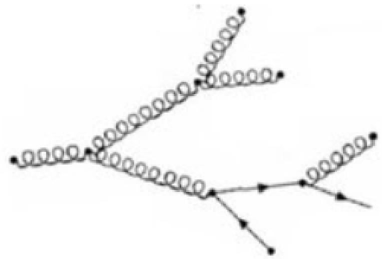
as well as the NKFIH 2019-2.1.11-TÉT-2019-00078, 2019-2.1.11-TÉT-2019-00050, 2019-2.1.6-NEMZKI-2019-00011 grants

Outline

Substructure of inclusive jets (pp collisions)



- Groomed jet substructures
- Generalized jet angularities

Flavor dependent substructure (pp collisions)

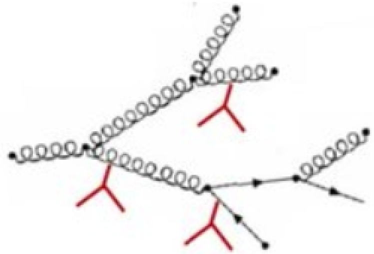
- D^0-meson and Λ_c-baryon fragmentation
- Dead cone, *R*-profile
- Charmed-jet groomed substructure

→ **Test of pQCD and hadronization models**

→ **Flavor-dependent production and fragmentation**

→ **Baseline for measurements in heavy-ion collisions**

Heavy-ion collisions



- Groomed jet substructures
- *N*-subjettiness, subjet fragmentation

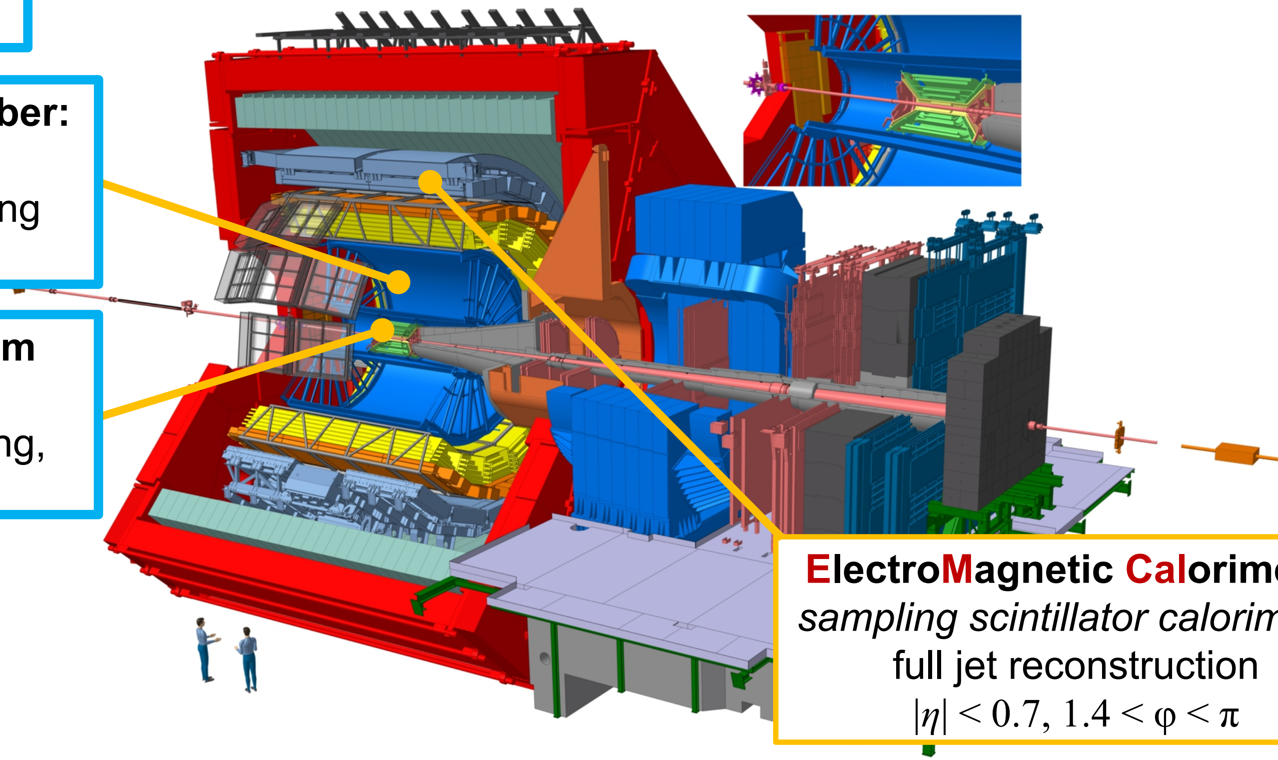
→ **Modification of jet fragmentation by the deconfined medium**

Jet measurements with ALICE

Central Barrel: $|\eta|<0.9$

Time Projection Chamber:
gas detector
charged-particle tracking
and identification

Inner Tracking System
silicon detectors
charged-particle tracking,
secondary vertex



ElectroMagnetic Calorimeter
sampling scintillator calorimeter
full jet reconstruction
$|\eta| < 0.7,\ 1.4 < \varphi < \pi$

Charged-particle jets

- Full azimuth coverage
- High spacial precision

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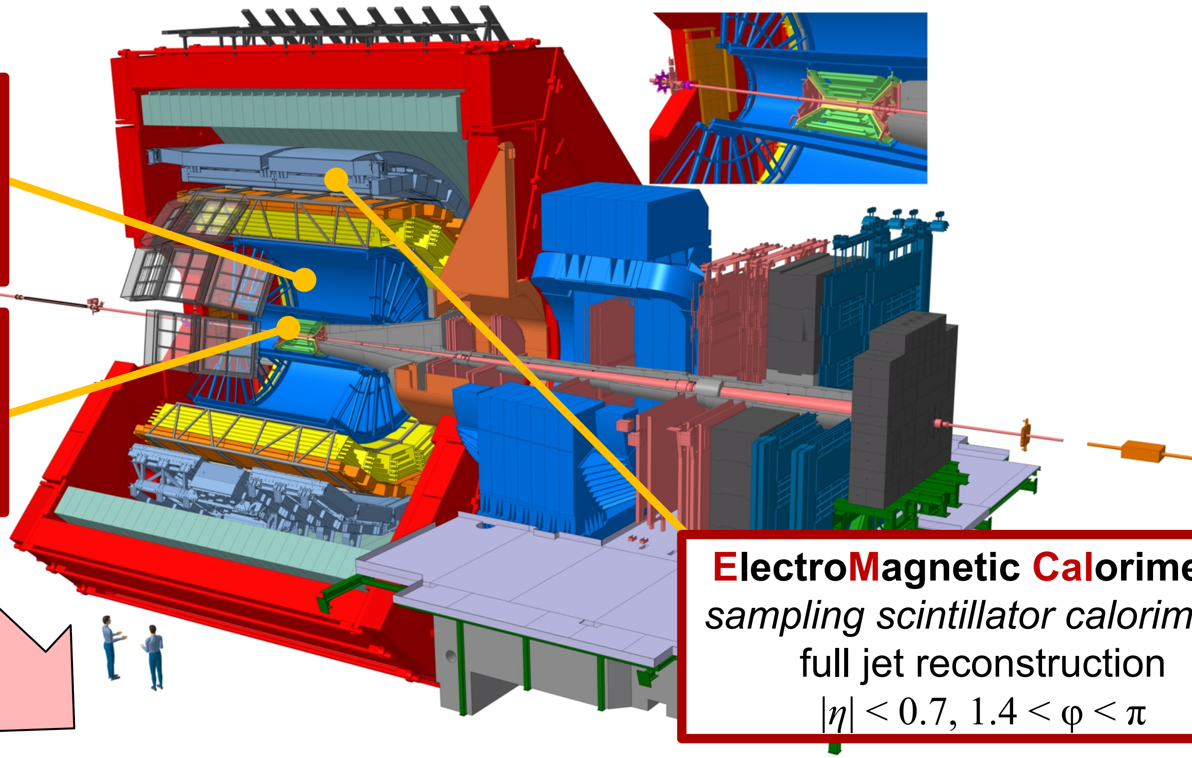

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Charged-particle jets

- Full azimuth coverage
- High spacial precision

Full jets

- Direct theory comparison
- Limited acceptance

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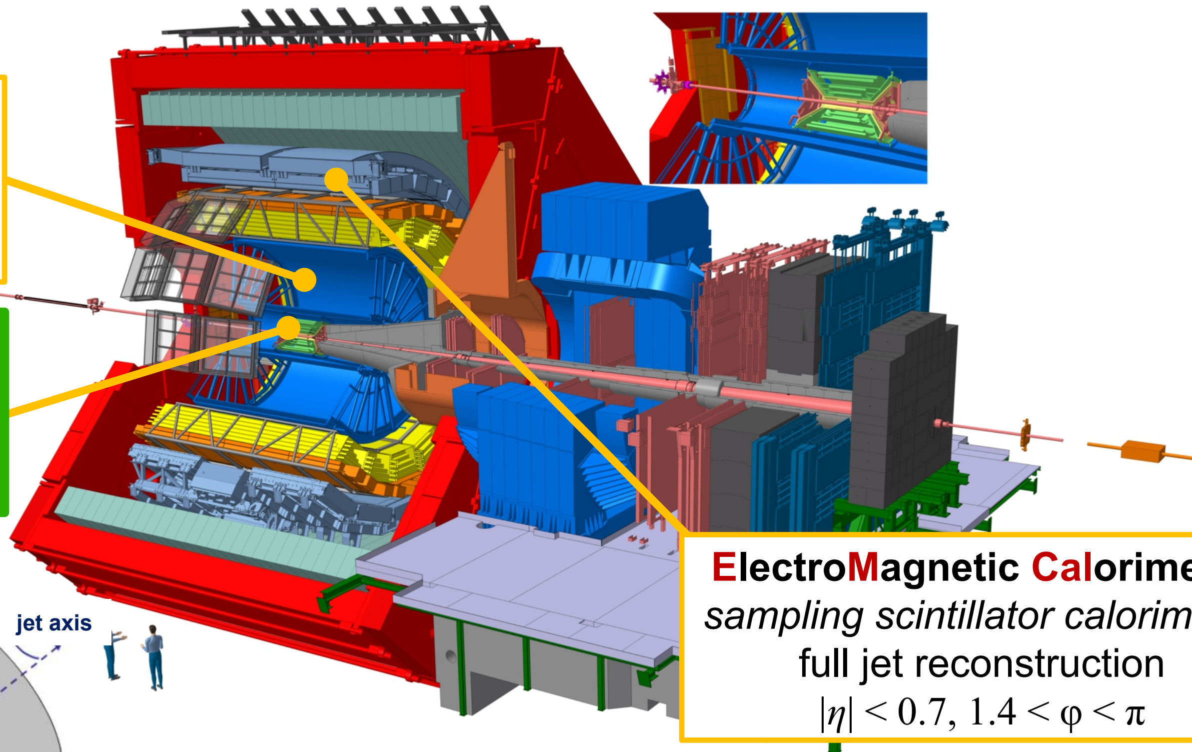

ElectroMagnetic Calorimeter
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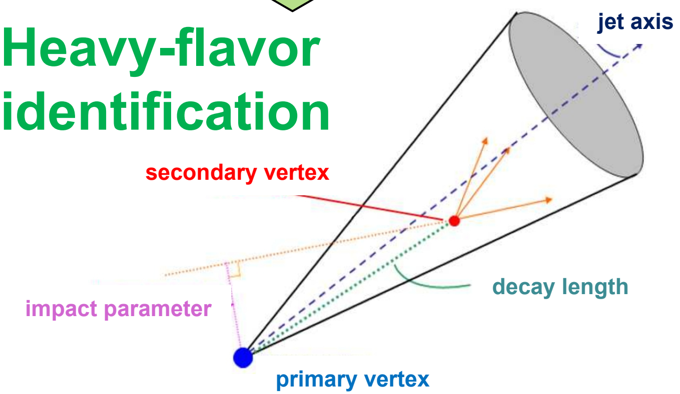
Heavy-flavor identification

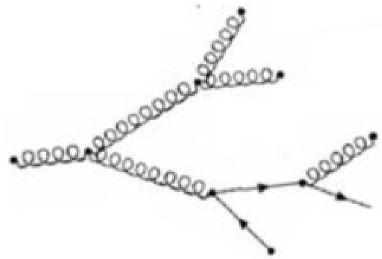


Lifetime of heavy flavor: **$c\tau$ (D) ~ 100-300 μm**
$c\tau$ (B) ~ 400-500 μm
Secondary vertex resolution: **< 100 μm**

Jet substructure in pp collisions

Substructure of inclusive jets (pp collisions)

- Groomed jet substructures
- Generalized jet angularities



Flavor dependent substructure (pp collisions)

- D^0-meson and Λ_c-baryon fragmentation
- Dead cone, *R*-profile
- Charmed-jet groomed substructure

→ **Test of pQCD and hadronization models**

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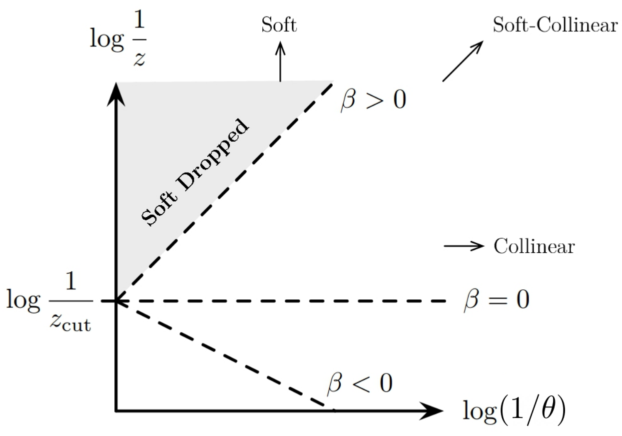
Heavy-ion collisions

- Groomed jet substructures
- *N*-subjettiness, subjet fragmentation

→ **Modification of jet fragmentation by the deconfined medium**

Groomed jet substructure

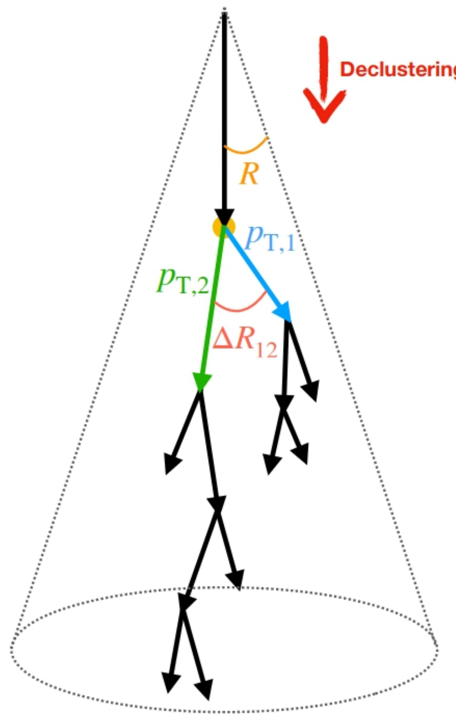
- Access to the hard parton structure of a jet
  - Mitigate influence from the underlying event, hadronization
  - Direct interface with QCD calculations
- Soft-drop grooming: Remove large-angle soft radiation
  - Recluster the jet with Cambridge-Aachen algorithm (angular ordered) and unwind the jet clusterization
  - Iteratively remove soft branches not fulfilling $z > z_{\mathrm{cut}}\theta^{\beta}$



Larkoski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

$$z = \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$

$$\theta = \frac{\Delta R_{12}}{R}$$



Groomed jet substructure

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  - Iteratively remove soft branches not fulfilling $z > z_{\mathrm{cut}}\theta^{\beta}$
- **Substructure variables**
  - **Groomed momentum fraction**

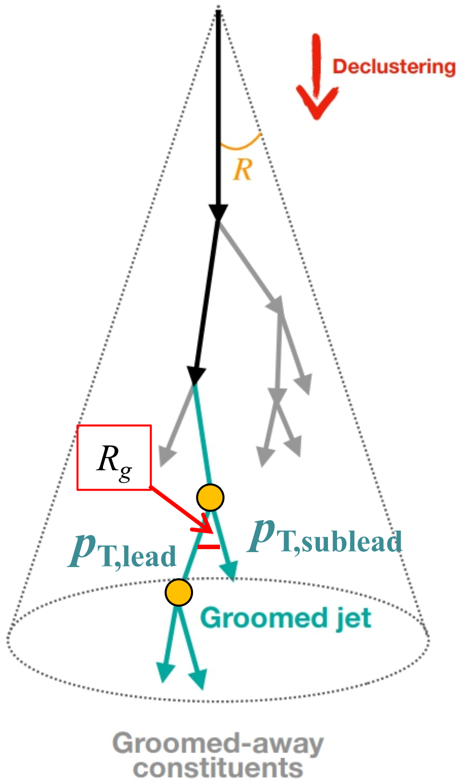
$$z_g = \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

  - **Groomed radius**

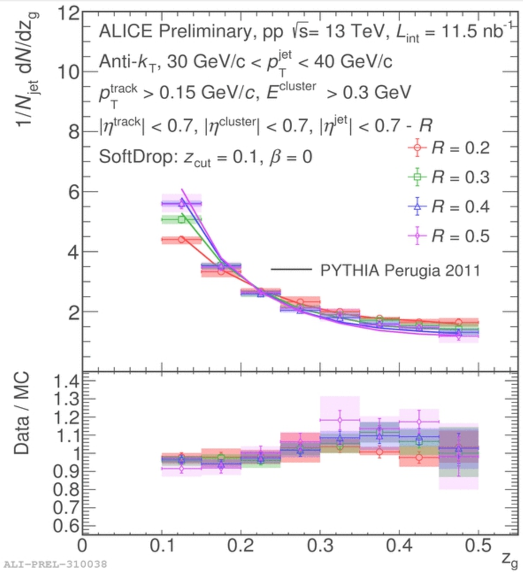
$$\theta_g \equiv \frac{R_g}{R}$$

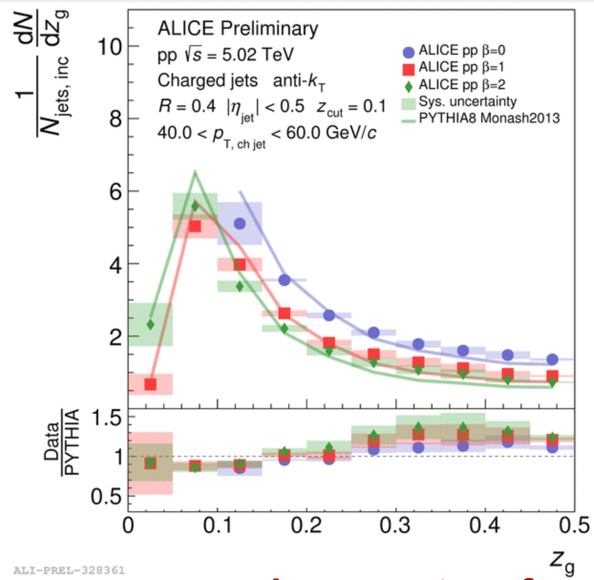
  - **Number of soft drop splittings**

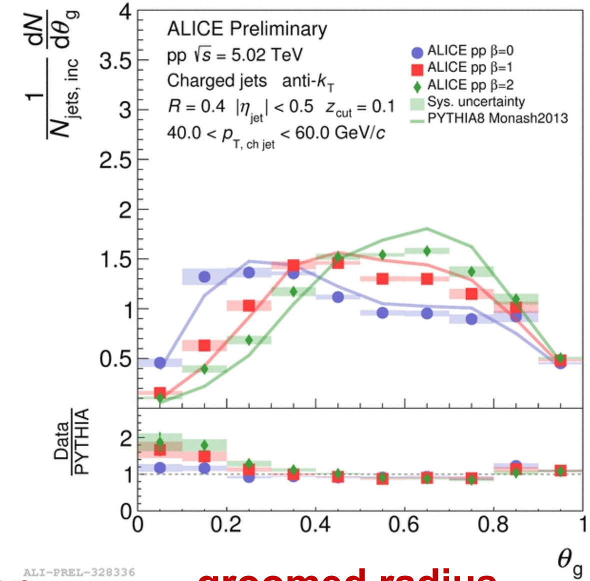
$$n_{\mathrm{SD}}$$



pp: Soft Drop grooming - z_g and θ_g







Groomed momentum fraction

Full jets pp $\sqrt{s}$ = 13 TeV

$30 < p_{T,jet} < 40$ GeV/c, $z_{cut} = 0.1$, $\beta = 0$

absolutely norm., no background sub.

groomed momentum fraction **groomed radius**

Charged-particle jets

pp $\sqrt{s}$ = 13 TeV, $40 < p_{T,jet} < 60$ GeV/c, $z_{cut} = 0.1$, $R = 0.4$

absolutely normalized

- Larger radii: more influence from non-perturbative effects
- Smaller β grooms soft splittings away → more collimated jets
- Trends reproduced relatively well by PYTHIA

→ ***test for pQCD predictions and constraints for non-perturbative effects***

Generalized jet angularities

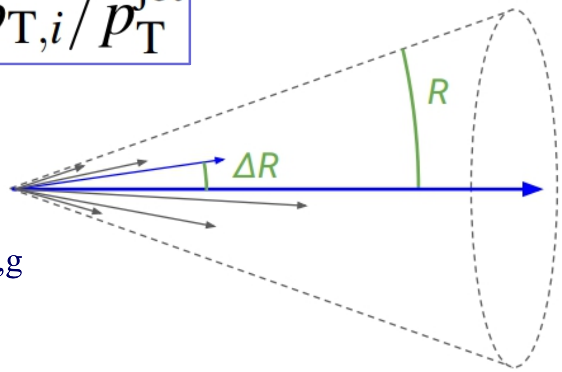
- Characterizes jet structure with transverse-momentum fraction and angular deflection of components
  - Weights associated to both, in a continuous manner

$$\lambda_\alpha^\kappa \equiv \sum_i z_i^\kappa \theta_i^\alpha$$

- Infrared and collinear safe for $\kappa=1, \alpha>0$
  - calculable from pQCD
  - Special cases: λ_1^1 Jet girth
    λ_2^1 Jet thrust

$$\theta_i \equiv \Delta R_i / R$$

$$z_i \equiv p_{\mathrm{T},i} / p_{\mathrm{T}}^{\mathrm{jet}}$$

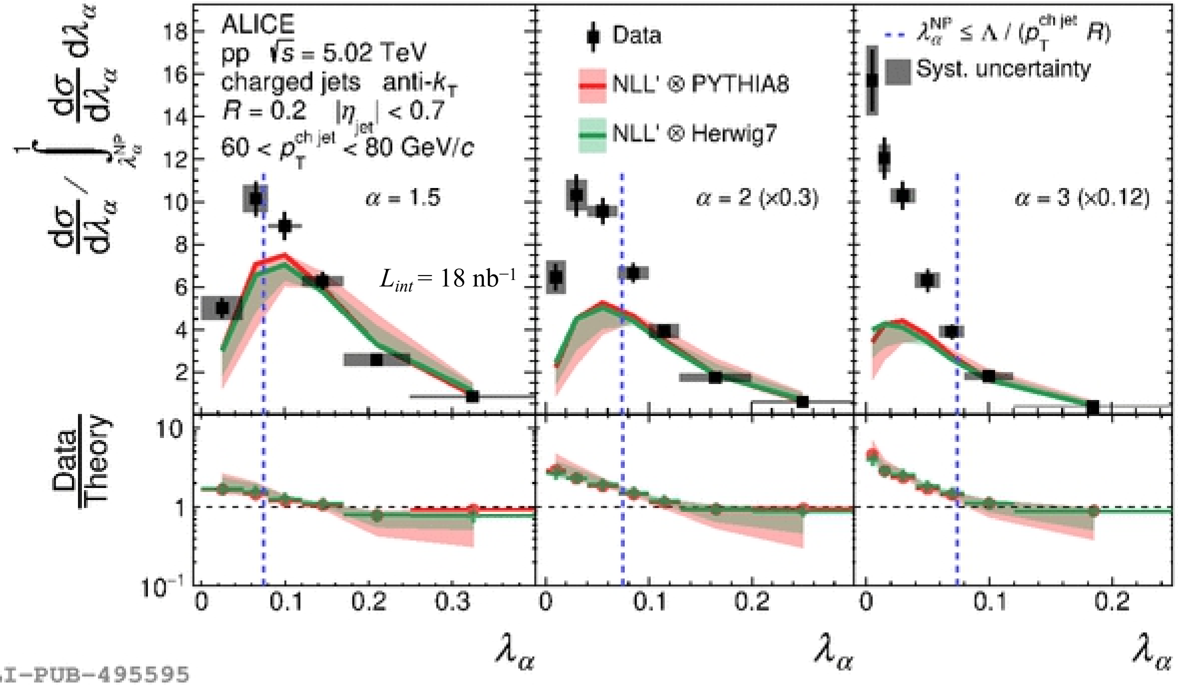


- systematic variation of α
- comparison of non-groomed λ_α and groomed-jet $\lambda_{\alpha,g}$

  => Provides constraints on models

  => Explores interplay between perturbative and nonperturbative QCD regime

pp: Generalized jet angularities

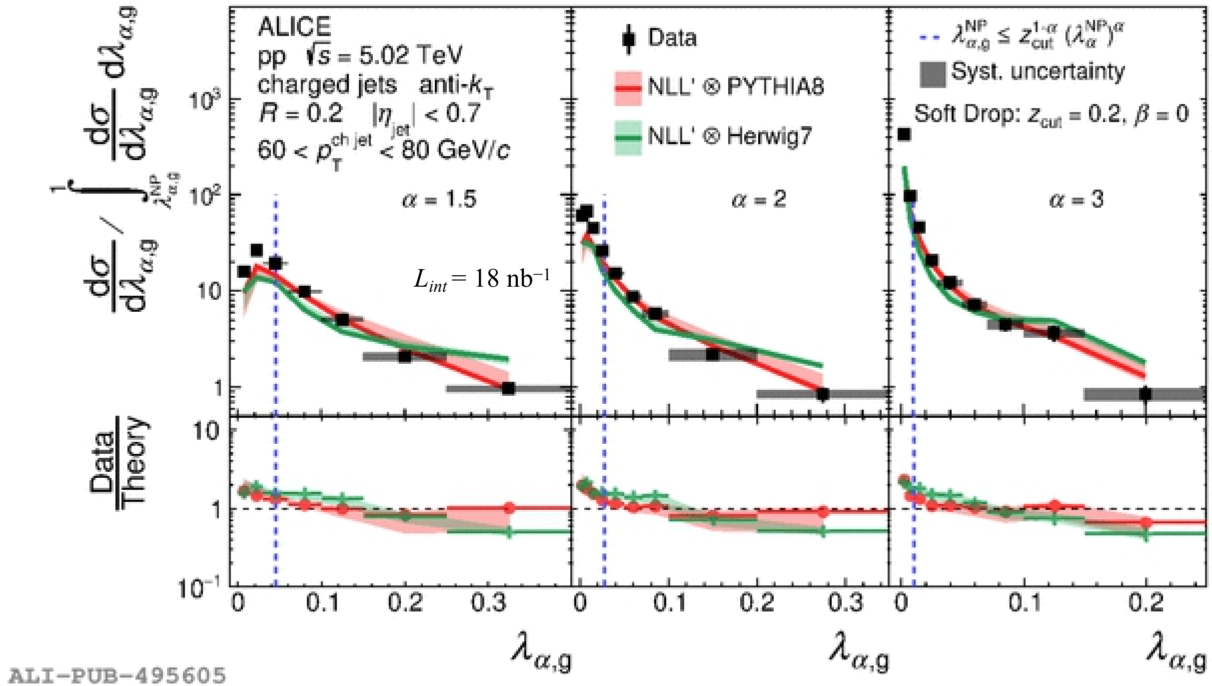


arXiv:2107.11303

NLL': Almeida et al. JHEP 04 (2014) 174

- First comparison of jet angularities to NLL' calculations at different α values
  - Full range of measurement: p_T^{chjet}/(GeV/c) ∈ [20, 100], R = 0.2, 0.4
  - Unfolded in p_T^{chjet} and λ_α => direct comparison to theory
  - **Large deviations in the non-perturbative large-α range**
  - Better agreement in the perturbative, small-α range

pp: Generalized jet angularities - groomed



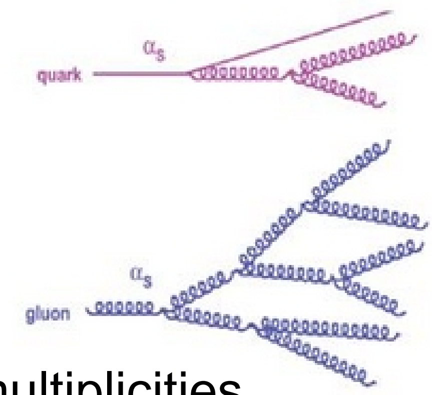
arXiv:2107.11303

NLL': Almeida et al. JHEP 04 (2014) 174

- First measurement of groomed-jet angularities
  - Full range of measurement: $p_T^{chjet}/(\text{GeV}/c) \in [20, 100]$, R = 0.2, 0.4
  - Unfolded in p_T^{chjet} and λ_α => direct comparison to theory
  - Vastly extended perturbative regime with grooming
  - **Good agreement with NNL' calculations**

Fragmentation of heavy-flavor

- $m_q > \Lambda_{QCD} \rightarrow$ perturbative production down to low jet p_T
- Heavy flavour conserved throughout the jet evolution
- Flavor-dependence of fragmentation:



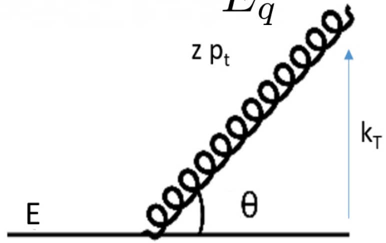
1) Color-charge effect

- Light jets are mostly gluon-initiated, while heavy-flavor jets are quark-initiated
- Couplings are different: qqg C_F~4/3 vs. ggg C_A~3
- Results in different shapes, momentum distributions, multiplicities

2) Mass-related effects

- **Heavy flavor fragments hard:** A large fraction of momentum is taken by the heavy hadron
- **Dead cone:** Forward emissions from radiators with large mass are suppressed

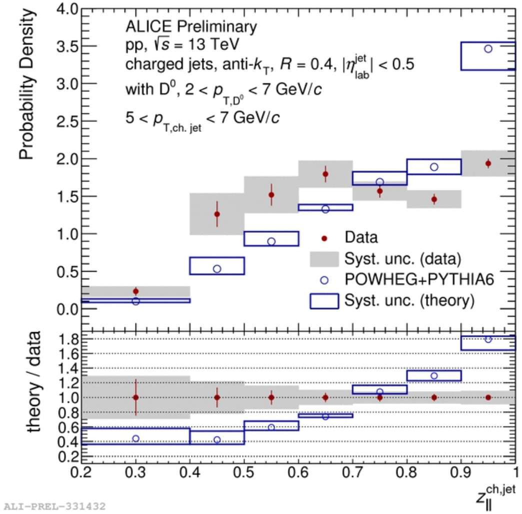
$$\theta < \theta_{\mathrm{DC}} = \frac{m_q}{E_q}$$



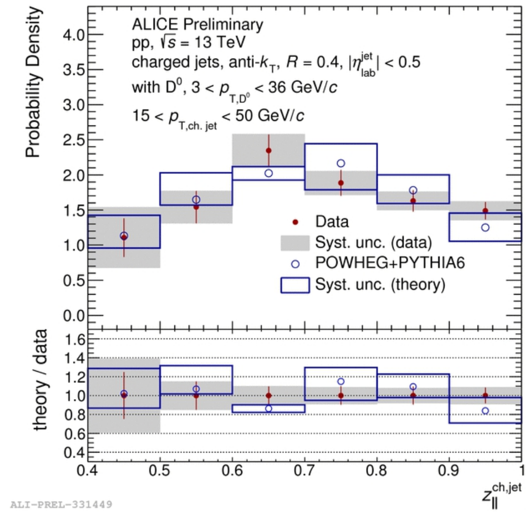
θ ~ k_T/zp_t

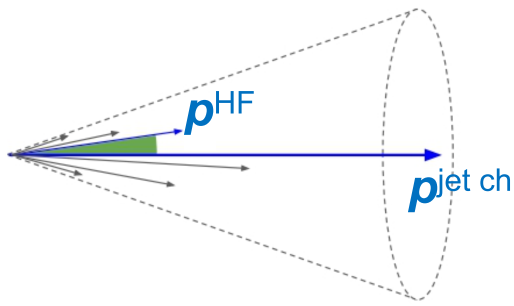
pp: Charm fragmentation - D-jet $z_{||}$

D⁰ in jets **5 < $p_T^{\text{ch,jet}}$ < 7 GeV/c**



15 < $p_T^{\text{ch,jet}}$ < 50 GeV/c



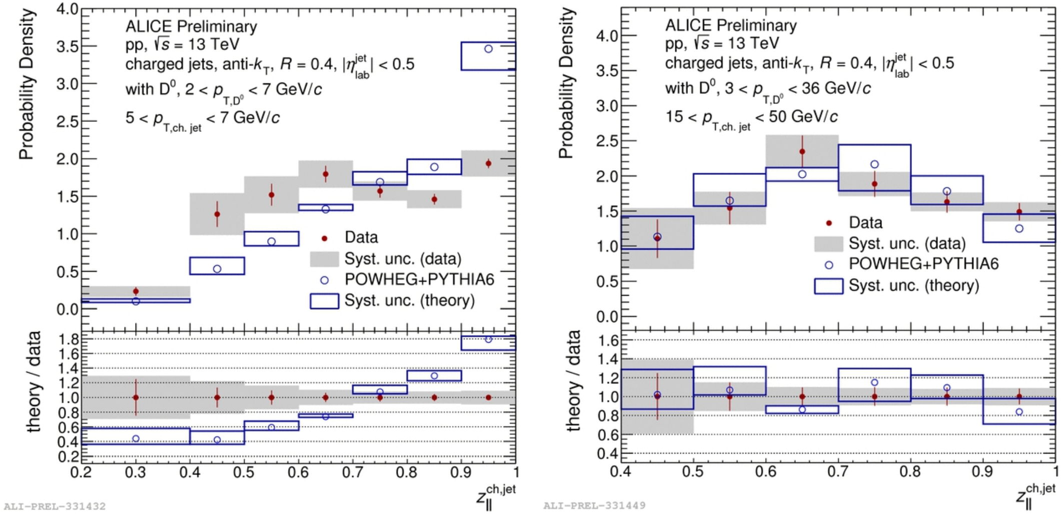


- **Parallel momentum fraction, pp $\sqrt{s}$ = 13 TeV**
  - Characteristic to heavy-flavor fragmentation
- **D⁰-meson fragmentation** is softer at high p_T than at lower p_T
  - POWHEG+PYTHIA6 predicts a stronger change towards low p_T

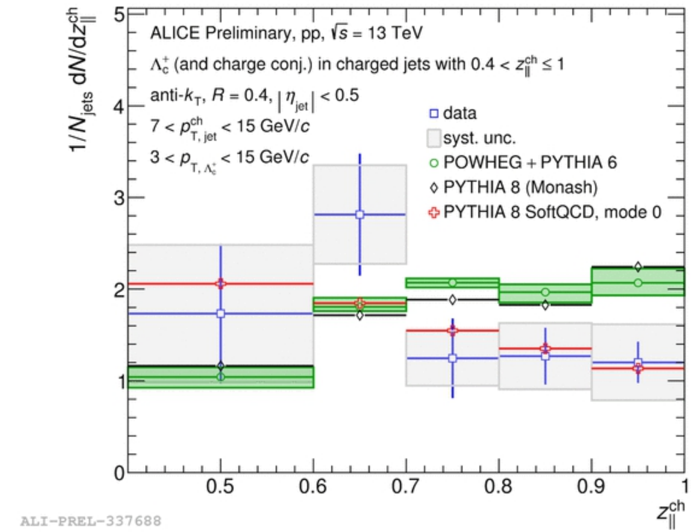
$$z_{||}^{\text{ch}} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

pp: Charm fragmentation - Λ_c-jet and D-jet $z_{||}$

D^0 in jets $5 < p_T^{ch,jet} < 7$ GeV/c $\quad$ $15 < p_T^{ch,jet} < 50$ GeV/c



Λ_c in jets $7 < p_T^{ch,jet} < 15$ GeV/c

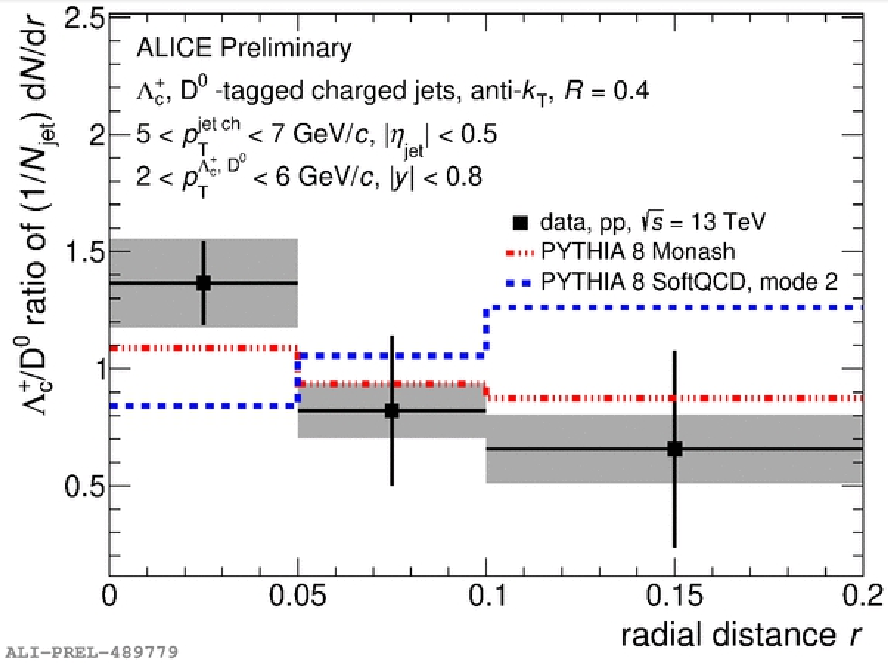


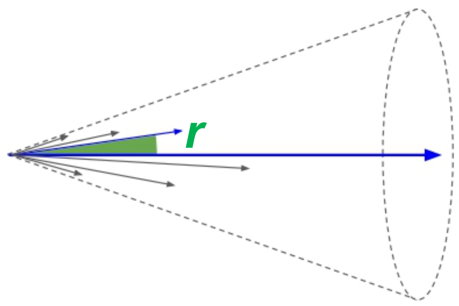
- **Parallel momentum fraction,** **pp $\sqrt{s} = 13$ TeV**
  - Characteristic to heavy-flavor fragmentation

$$z_{||}^{ch} = \frac{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{HF}}}{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{jet ch}}}$$

- **D^0-meson fragmentation** is softer at high p_T than at lower p_T
  - POWHEG+PYTHIA6 predicts a stronger change towards low p_T
- **Λ_c fragmentation:** similar trends (different p_T range!)
  - PYTHIA8 with SoftQCD settings performs well with Λ_c
  - **Opportunity to compare baryon to meson fragmentation**

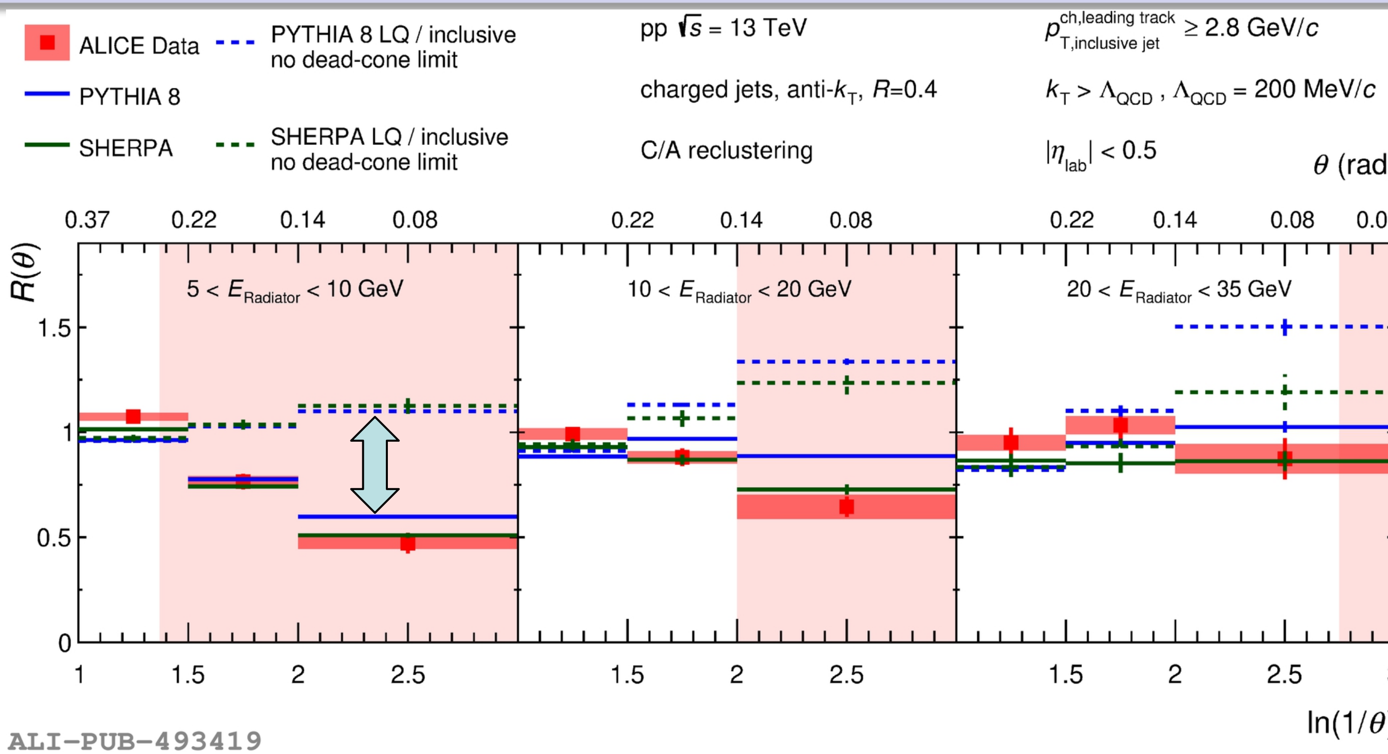
pp: Charm fragmentation - Λ_c , D-jet r-shape



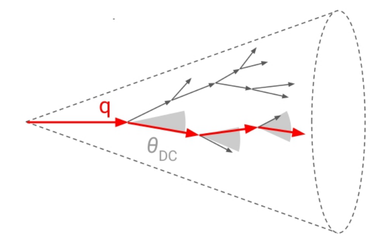


- **Radial angular distance distribution of a hadron from the jet axis, pp $\sqrt{s}$=13 TeV**
  - Sensitive to different hadronisation mechanisms
  - Complementary to fragmentation function
- **Λ_c fragments closer to jet axis than D^0**
  - Better described by Monash than enhanced colour reconnection

pp: Dead cone effect in ALICE



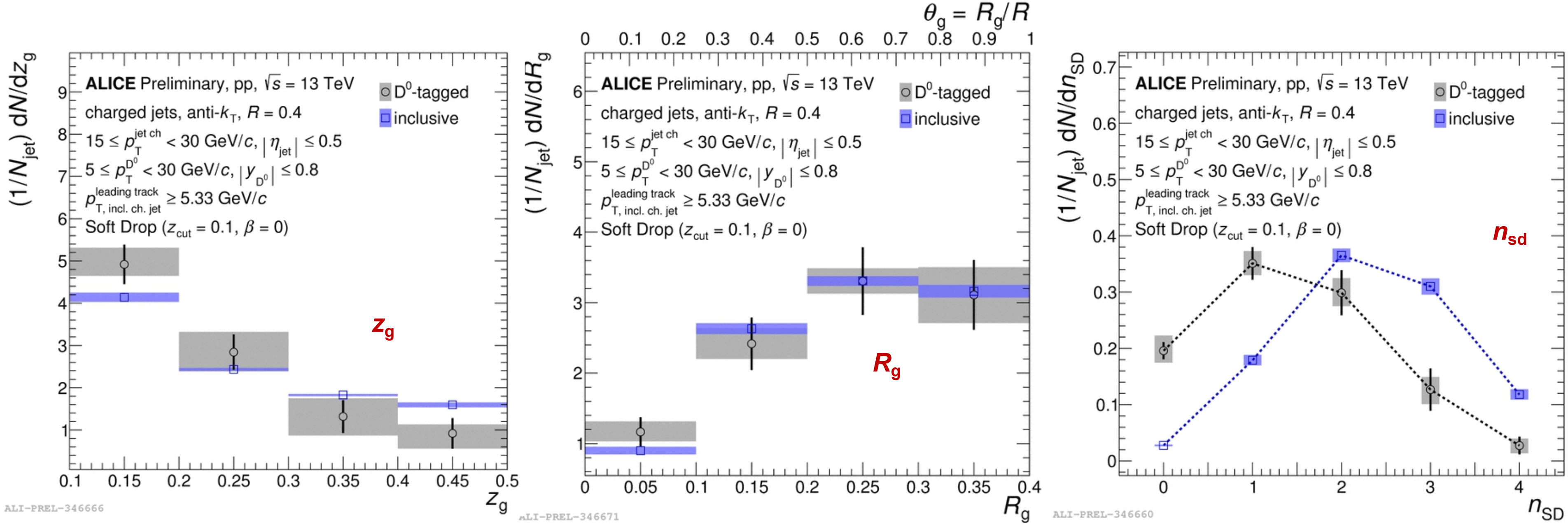
arxiv:2106.05713



- **D-tagged to inclusive ratios vs. ln(1/θ) at $\sqrt{s}$=13 TeV**
- Significant suppression of low-angle splittings in D-tagged jet

  => First direct measurement of the dead cone in hadronic collisions
- Effect decreases toward higher energy of the radiator ($\rightarrow \theta > m_q/E_q$)

pp: D-jet substructure - z_g, R_g, n_{SD}

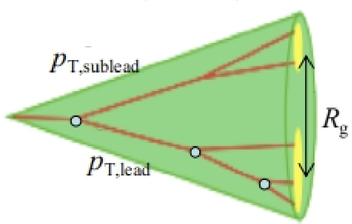


ALICE-PUBLIC-2020-002

- **D⁰-tagged charged-jet groomed substructuce**
  pp $\sqrt{s}$ = 13 TeV, $z_{cut} = 0.1, \beta = 0$
- n_{SD} : charm jets typically have less hard splitting than light jets

→ **Consistent with harder heavy-flavor fragmentation**
(mass and color charge effects)

$$z_g = \frac{p_{T,sublead}}{p_{T,lead} + p_{T,sublead}}$$



Jet substructure in Pb-Pb collisions

Substructure of inclusive jets (pp collisions)

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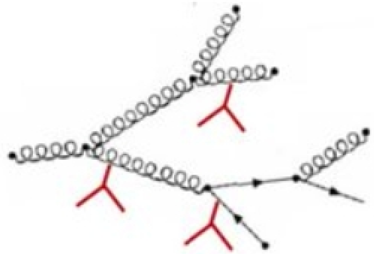
Heavy-ion collisions



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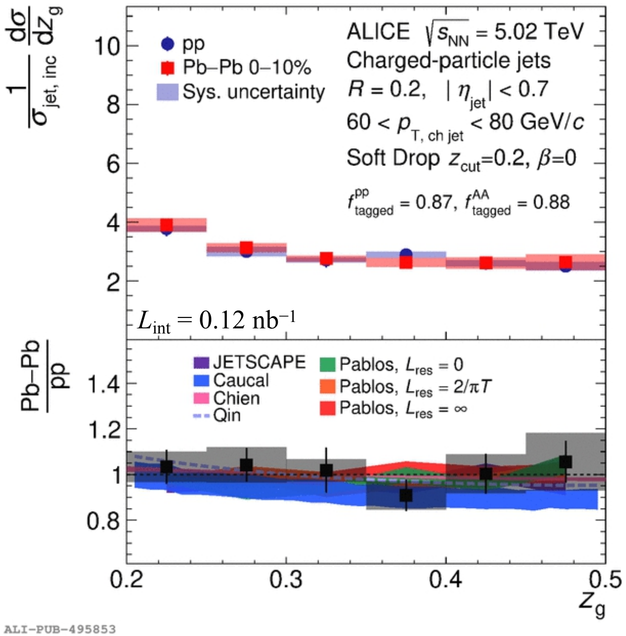
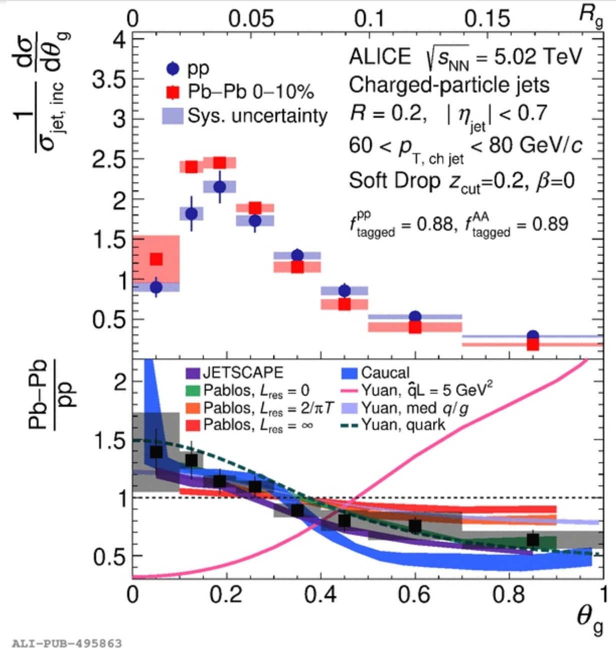
→ **Modification of jet fragmentation by the deconfined medium**

Pb-Pb: groomed jets - z_g and θ_g



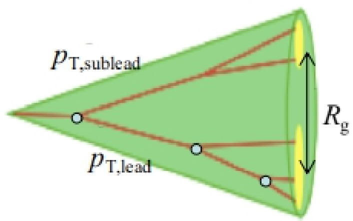
groomed momentum fraction



groomed radius

arXiv:2107.12984

$$z_g = \frac{p_{T,\text{sublead}}}{p_{T,\text{lead}} + p_{T,\text{sublead}}}$$



Charged-particle jets, fully unfolded, Pb-Pb $\sqrt{s_{NN}}$ = 5 TeV $z_{cut} = 0.2$, R = 0.2

Combinatorial background suppressed using event-wise constituent subtraction

- z_g: no effect of interaction of the jet shower with medium
- θ_g: suppression of large angles, enhancement of small angles => medium filters out wider subjets
- Models with incoherent energy loss as well as gluon filtering qualitatively describe data

Subjets - access radiation patterns

N-subjettiness

$$\tau_N = \frac{1}{p_{\mathrm{T}}^{\mathrm{chjet}} R} \sum_k p_{\mathrm{T},k} \min(\Delta R_{1,k}, ..\Delta R_{N,k})$$

$\tau_N \sim 1$ if number of subjet prongs > *N* ,

$\tau_N \sim 0$ otherwise

- τ_2/τ_1 distribution: occurrence of 2-pronged vs. 1-pronged jets

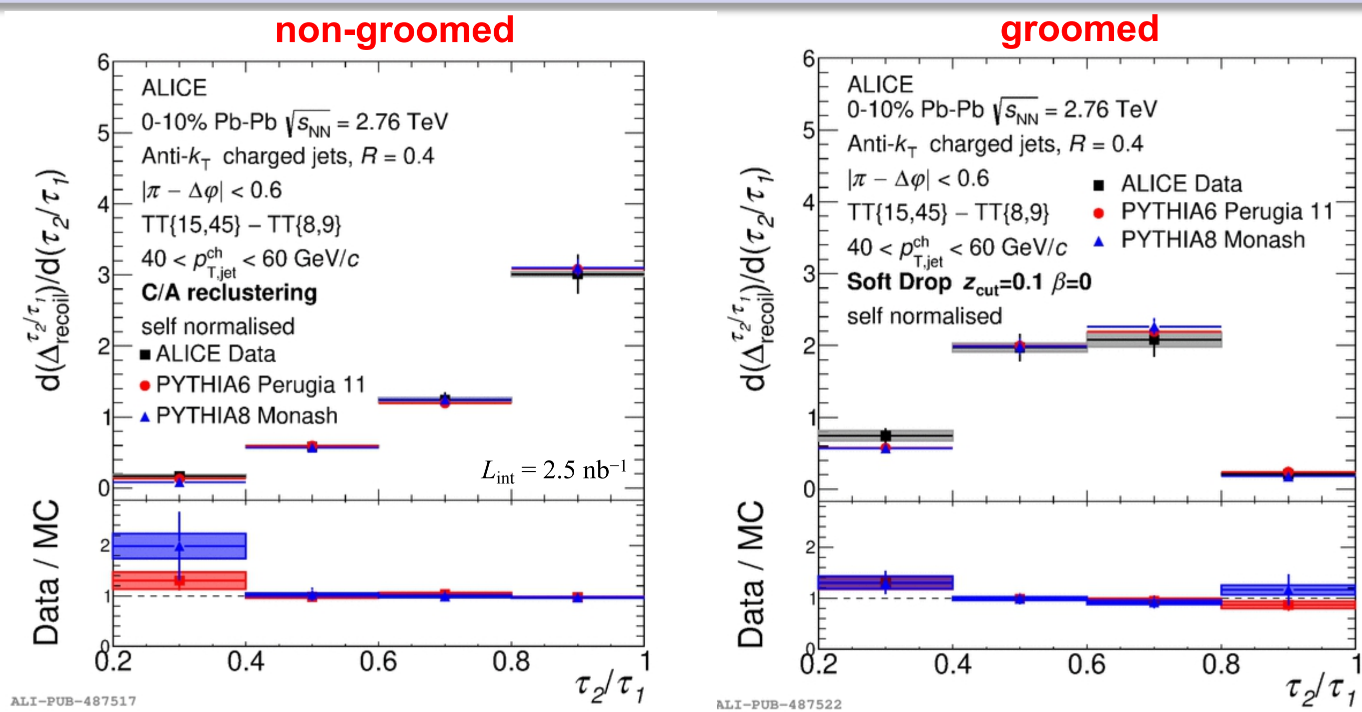
Subjet fragmentation

- Recluster jets using anti-k_{T} with a resolution parameter $r < R$
- Characterize leading subjets with momentum fraction

$$z_r = \frac{p_{\mathrm{T}}^{\mathrm{ch,subjet}}}{p_{\mathrm{T}}^{\mathrm{ch,jet}}}$$

- **Subjet properties are sensitive to radiation patterns within a jet**

Pb-Pb: *N*-subjettiness



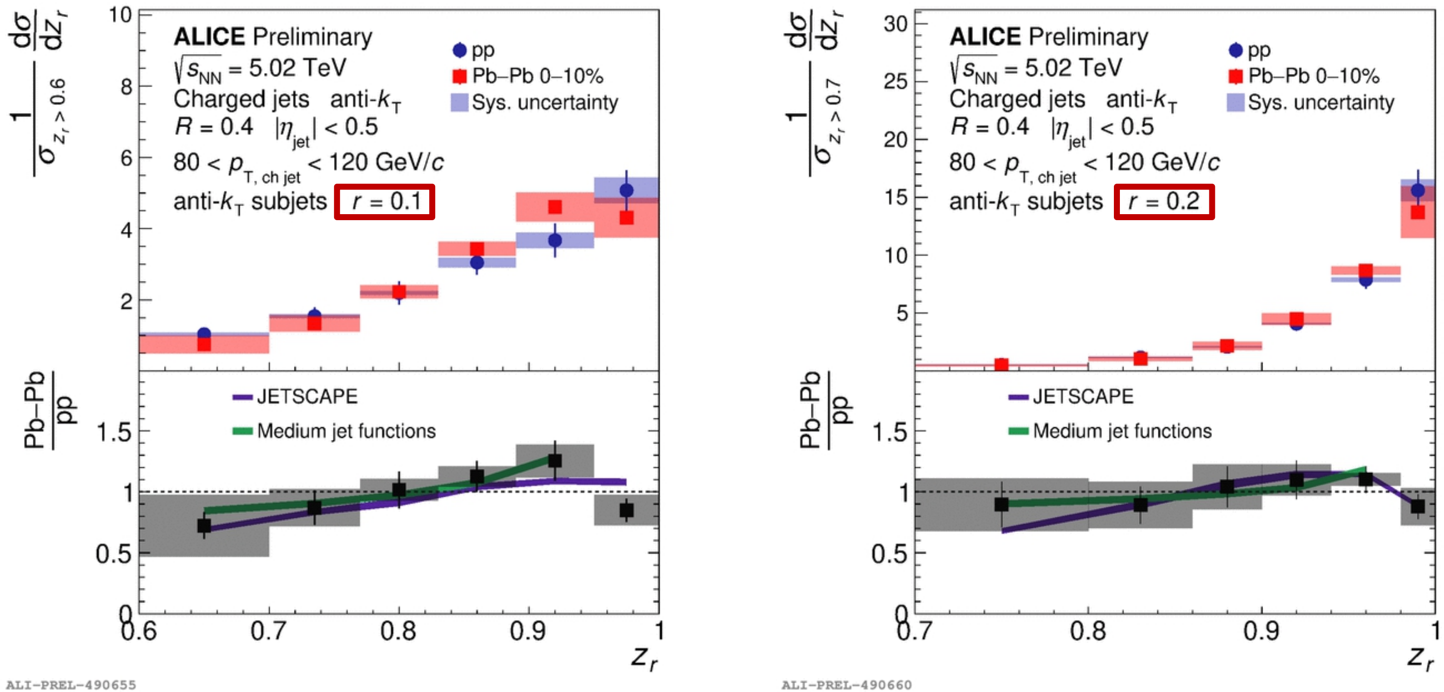
arXiv:2105.04936

1st measurement of *N*-subjettiness in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

- Fully corrected τ_2/τ_1 distributions (from recoil jets, unbiased towards lower $p_{T,chjet}$)
- Subjet axes determined using C/A-reclustering: slight deviation from PYTHIA8
- When C/A reclustering with soft-drop grooming applied:

No modification within current precision compared to PYTHIA

Pb-Pb: Subjet fragmentation



Subjet fragmentation z_r in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- $z_r \sim 1$ is quark-dominated
- **Hints of modification** for r = 0.1 subjets
- Consistent with no modification for r = 0.2 subjets
- **Consistent with model predictions**

Summary

- **pp collisions**- test of pQCD evolution and hadronization
  - Grooming techniques separate hard pQCD processes from soft radiation
  - Generalized angularities directly test of pQCD calculations as well as non-perturbative shape functions
- **Charmed jets** - a handle on fragmentation without reclustering
  - Direct access to fragmentation without grooming ($z_{||}$, R-shapes)
  - Means to explore flavor and mass-dependent fragmentation: First observation of the dead cone in hadronic collisions
- **Pb-Pb collisions** - jet modification by the medium
  - Groomed substructure observables, N-subjettiness, subjet-fragmentation
  - Test different aspects of medium modification on jet evolution, separation of soft and hard components

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Just a fraction of ALICE substructure measurements - much more out there

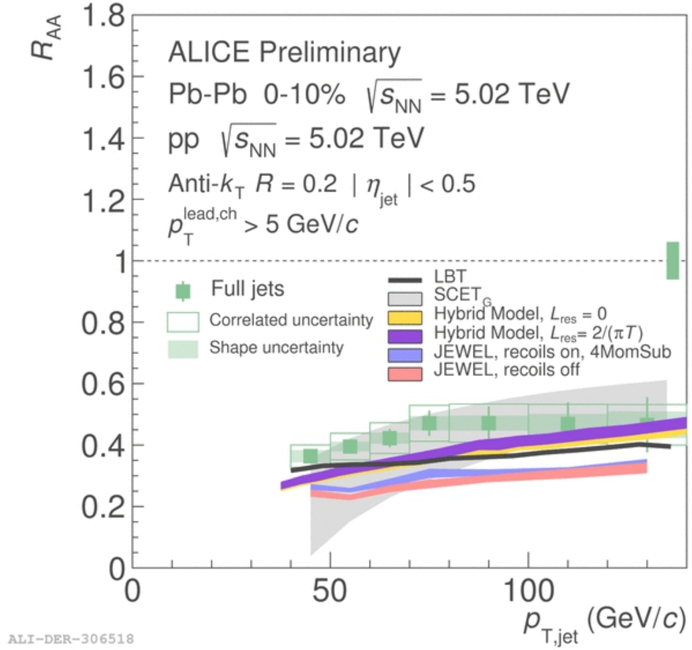
High-precision Run3 data: beauty-jets, nuclear modification in details...

Thank you!

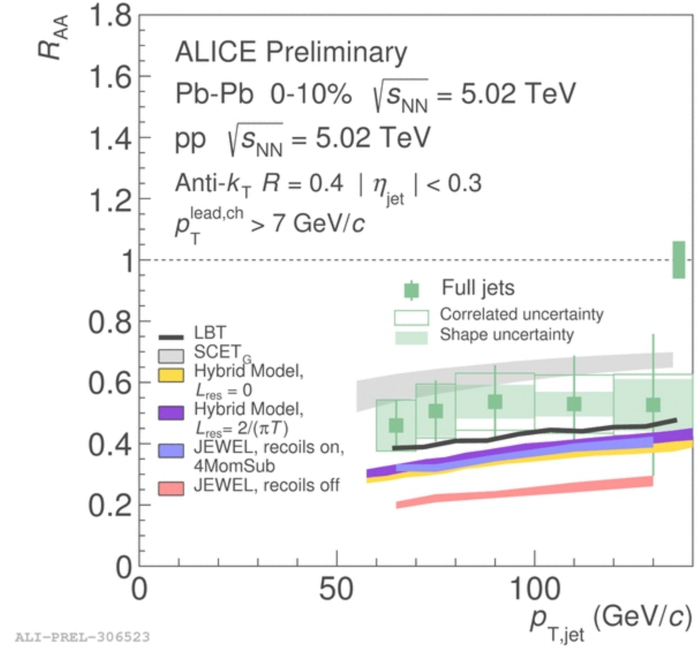
This work has been supported by the Hungarian NKFIH OTKA FK131979 and K135515
as well as the NKFIH 2019-2.1.11-TÉT-2019-00078, 2019-2.1.11-TÉT-2019-00050, 2019-2.1.6-NEMZKI-2019-00011 grants

Jet suppression in Pb-Pb

narrow jets, R=0.2



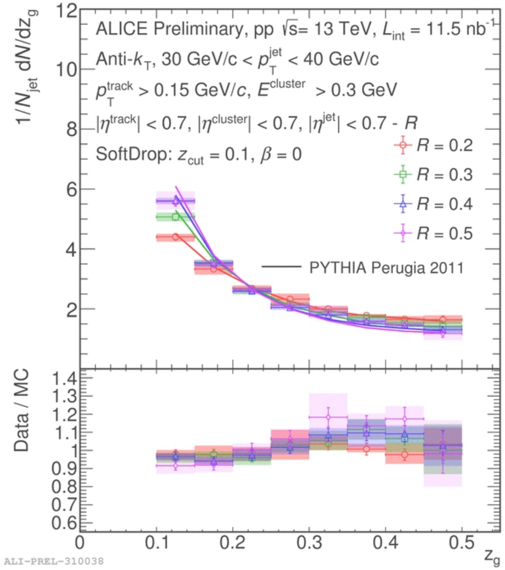
wide jets, R=0.4



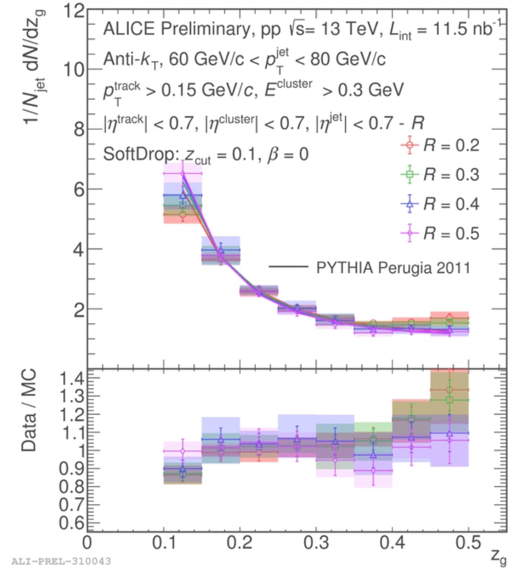
- Measurement down to p_T = 40 GeV/c => redistribution of energy
- Only weak dependence seen in data on jet resolution R
- Challenge to some models: stronger R dependence predicted than in data

Soft Drop grooming: z_g vs. jet R

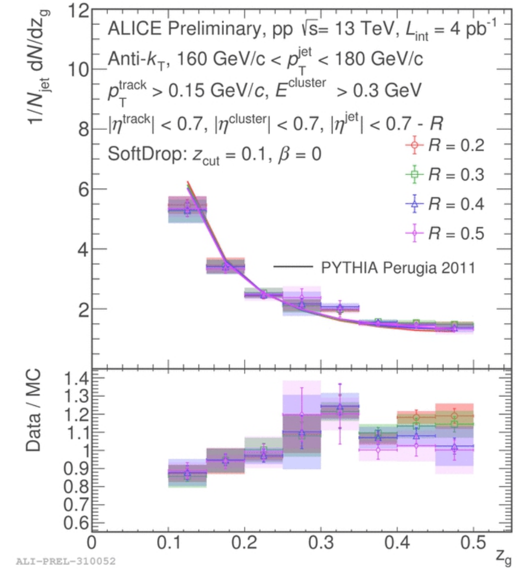
30-40 GeV/*c*



60-80 GeV/*c*

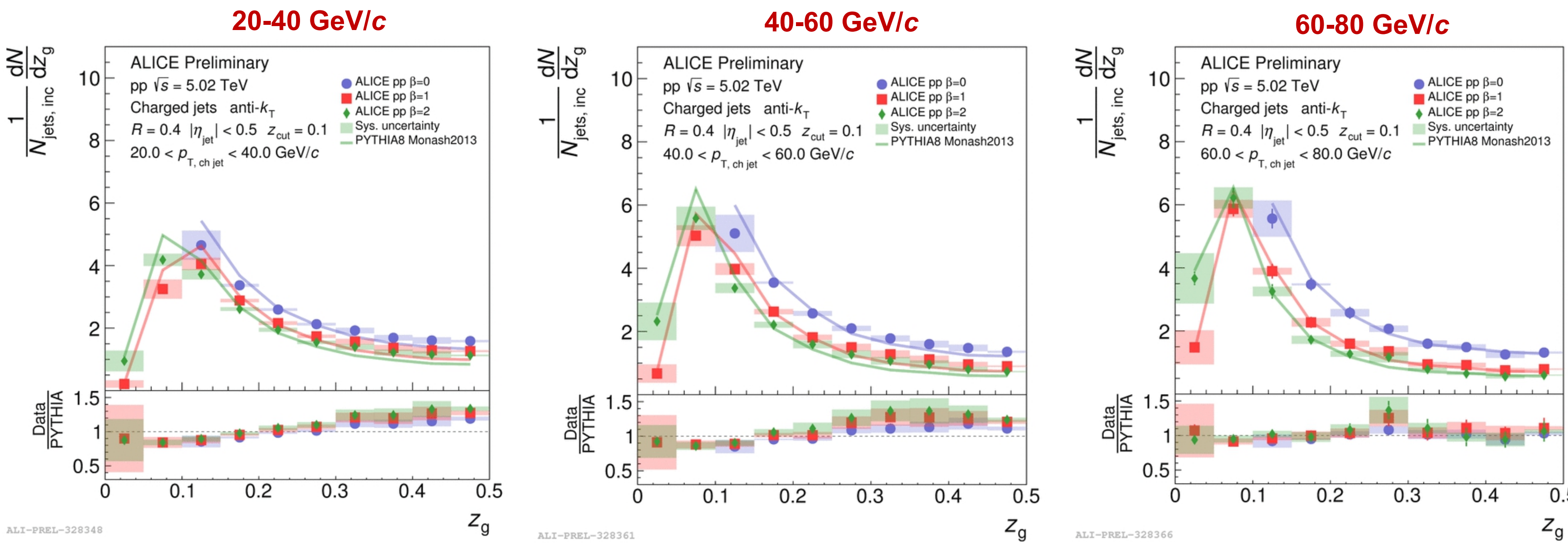


160-180 GeV/*c*



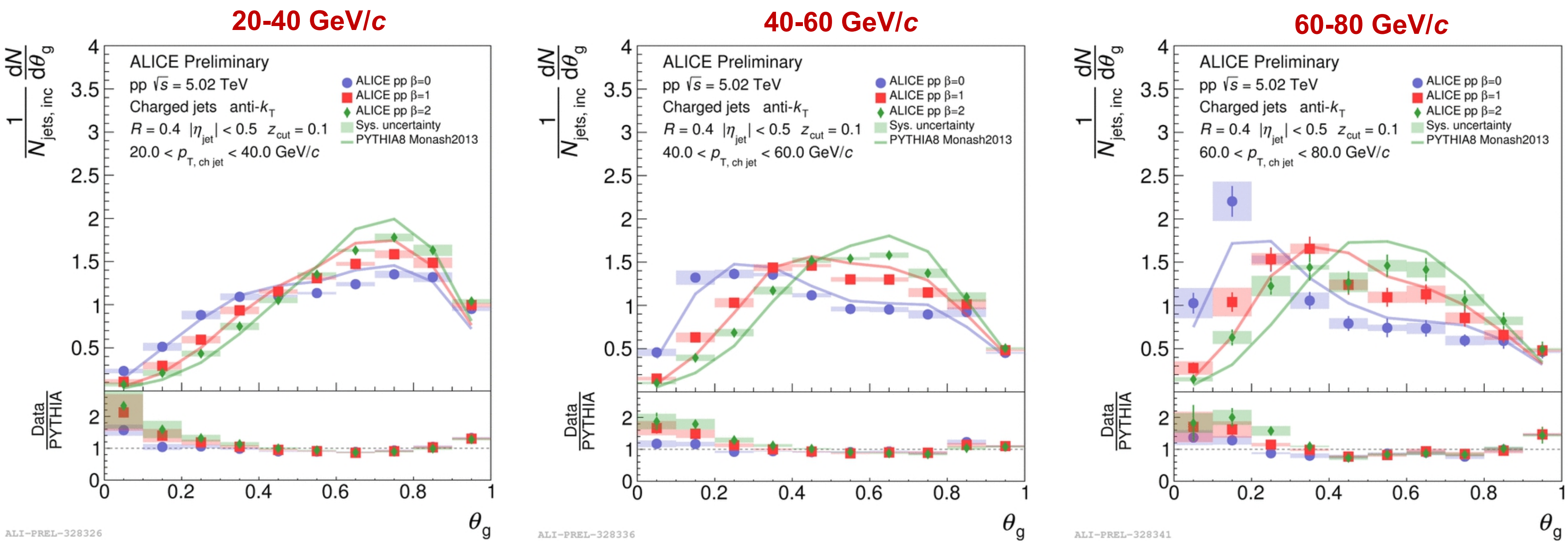
- **Full-jet groomed momentum fraction in pp collisions** at $\sqrt{s} = 13$ **TeV**
  $z_{cut} = 0.1$, $\beta = 0$, absolutely normalized, no background subtraction
- At low p_T: small radii jets tend to split more symmetrically
  larger radii: higher sensitivity to non-perturbative effects
- Slight p_T-dependence for small radii
- Trends reproduced well by PYTHIA

Soft Drop grooming: z_g vs. β



- **Charged-particle jet groomed momentum fraction in pp collisions** at $\sqrt{s} = 13$ **TeV**
  $z_{cut} = 0.1$, $R = 0.4$, absolutely normalized
- A weak p_T-dependence is present
- Trends reproduced relatively well by PYTHIA

Soft Drop grooming: θ_g vs. β

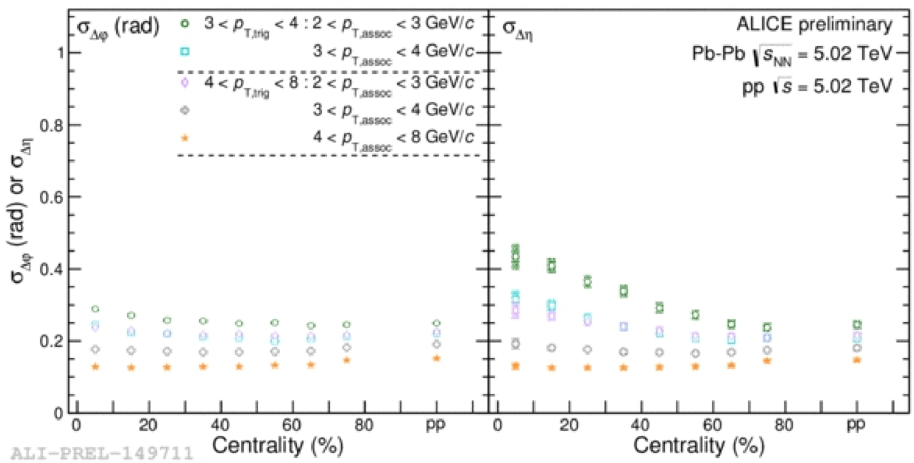


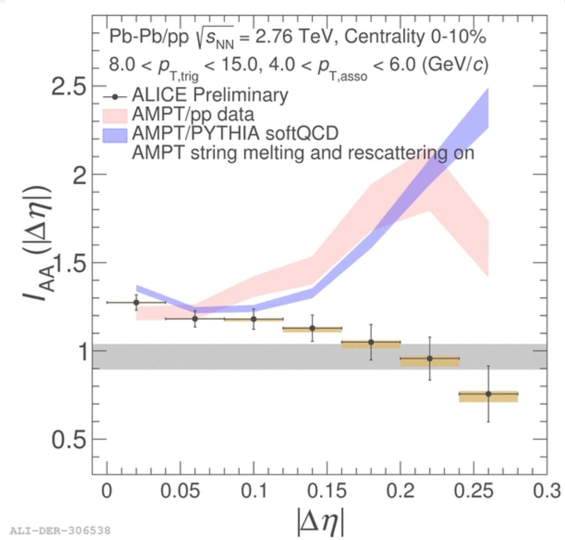
- **Charged-particle jet groomed radius in pp collisions** at $\sqrt{s}$ = **13 TeV**
  $z_{cut} = 0.1$, R = 0.4, absolutely normalized

- Smaller β grooms soft splittings away → more collimated jets
- Trends reproduced relatively well by PYTHIA

→ *possibility to explore contributions from partonic and hadronic stages*

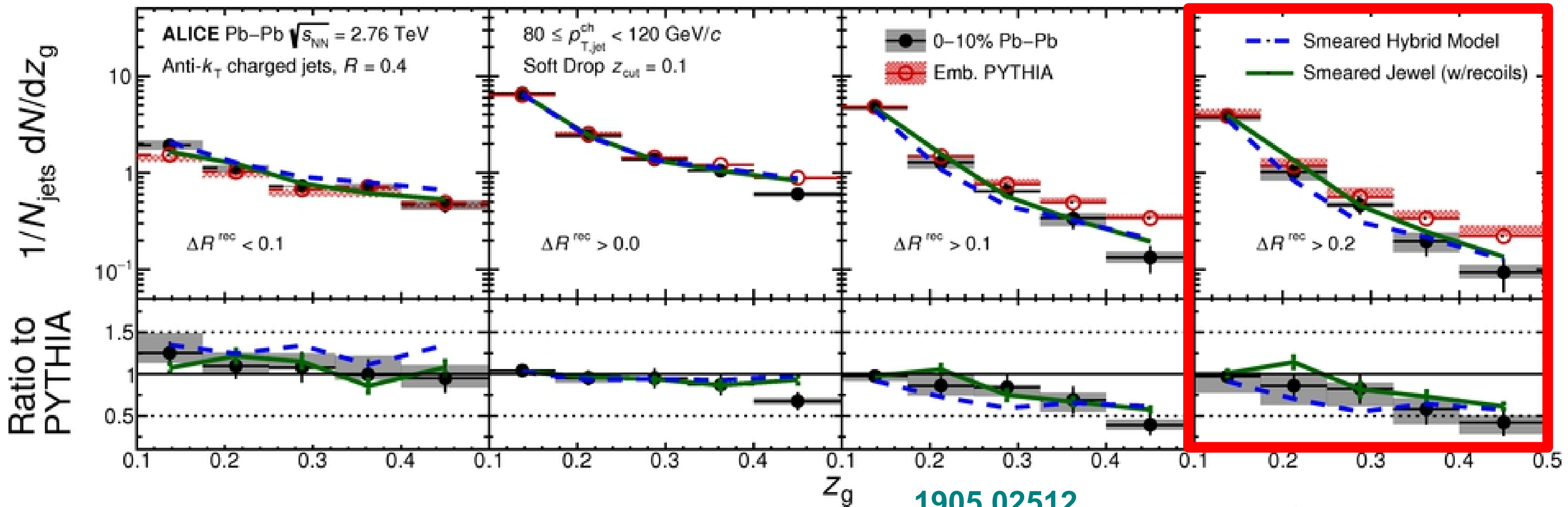
Jet-medium interactions





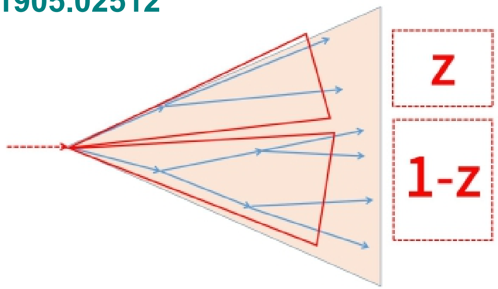
- **Low p_T**: Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of **central** angular correlation peaks in the **Δ*η*** direction
  - Understanding: rescattering with radial flow (AMPT)
- **Higher p_T**: Azimuthal h-h correlations, $I_{AA} = Y_{AA}/Y_{pp}$
  - **Narrowing** of the peak in **central** events in the **Δ*η*** direction
  - Jet structure modifications? No proper understanding by models.

Jet Substructure in Pb-Pb



1905.02512

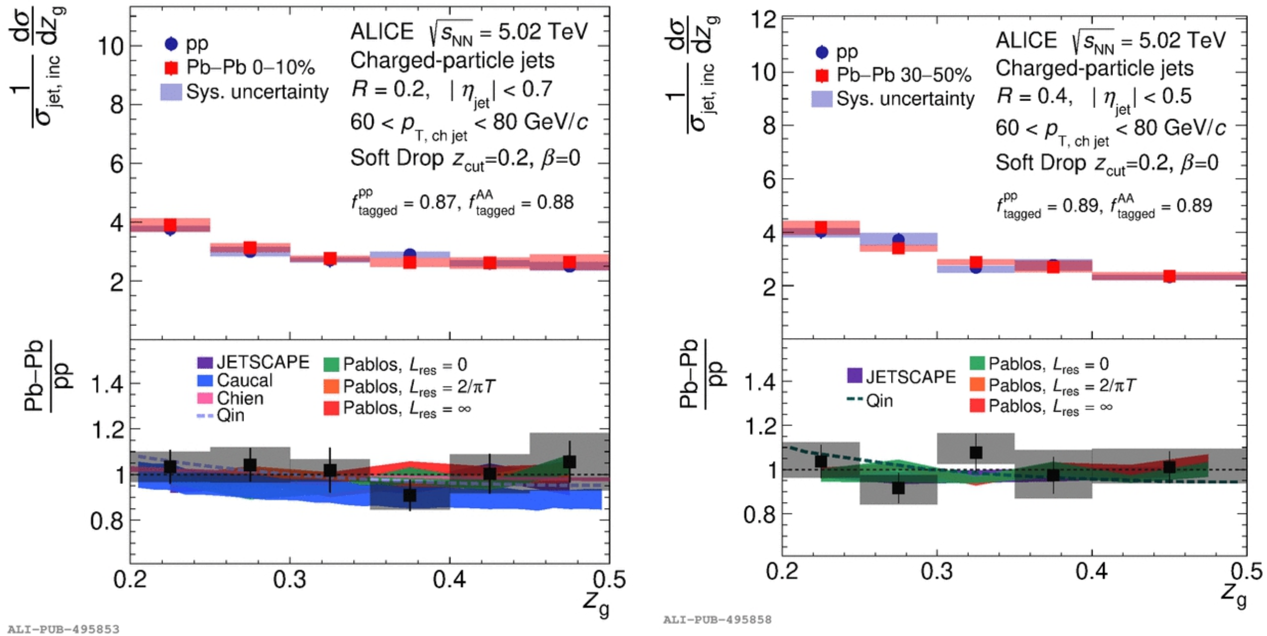
- First intra-jet splitting z_g
  - At small angles (ΔR < 0.1): consistent z_g distributions in Pb-Pb and vacuum
  - At large angles (ΔR > 0.2): z_g distributions are steeper in medium than in vacuum



$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- **Early jet development influenced by medium**

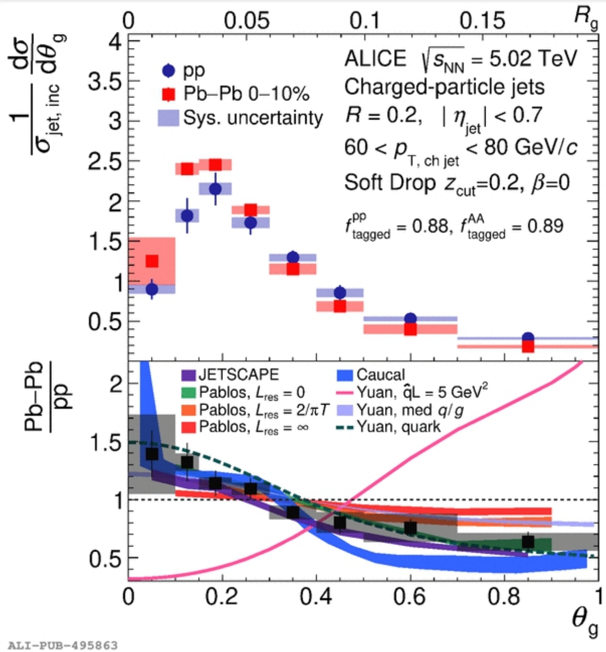
Pb-Pb: groomed jets - z_g

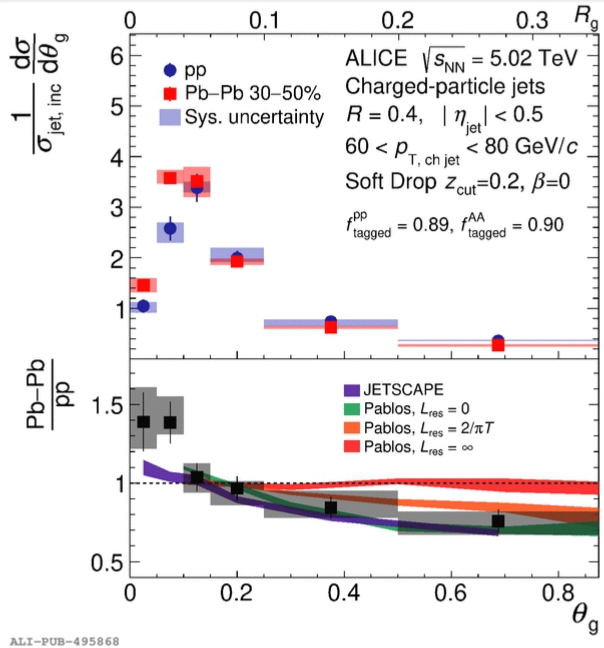


arXiv:2107.12984

- **Charged-particle jet groomed momentum fraction**
  Fully unfolded, Pb-Pb $\sqrt{s_{NN}}$ = 5 TeV $z_{cut} = 0.2$, R = 0.2
- Combinatorial background suppressed using event-wise constituent subtraction
- Consistent with no modification:
  interaction of the jet shower with medium does not affect z_g

Pb-Pb: groomed jets - θ_g

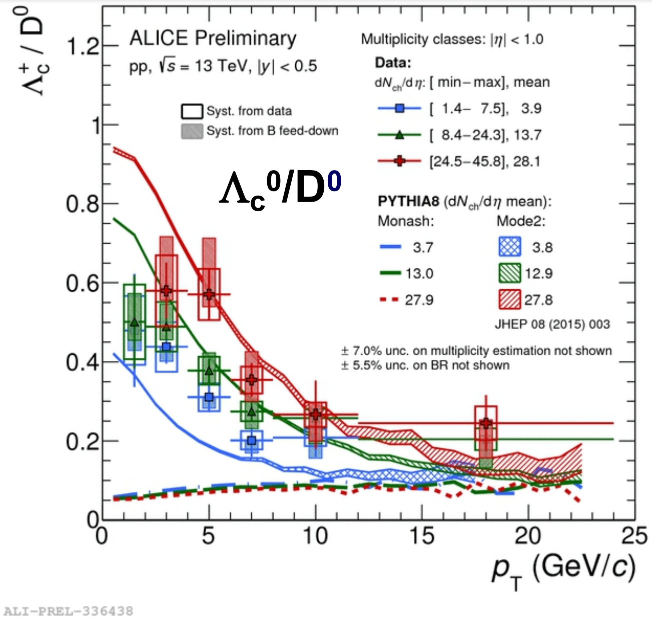


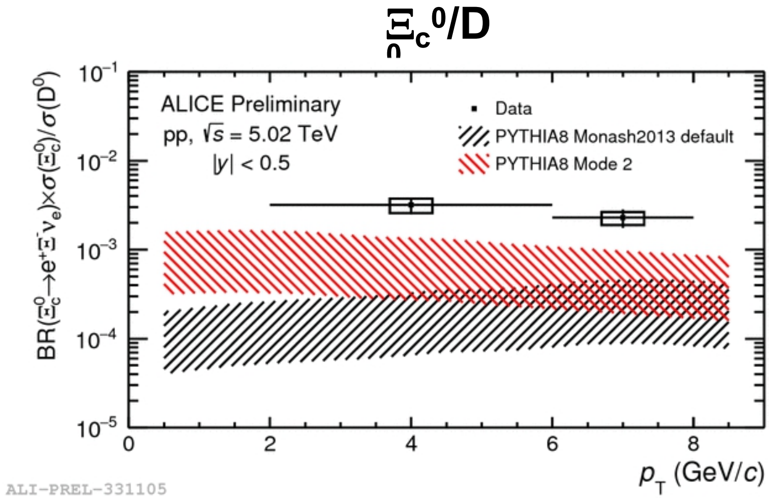


arXiv:2107.12984

- **Charged-particle jet groomed radius**
  Fully unfolded, Pb-Pb $\sqrt{s_{NN}} = 5$ TeV $z_{cut} = 0.2$, R = 0.2
- Suppression of large angles and enhancement of small angles
  => medium filters out wider subjets
- Models with incoherent energy loss as well as gluon filtering qualitatively describe data

Baryon-to-meson ratio: Λ_c^+/D^0, Ξ_c^0/D^0



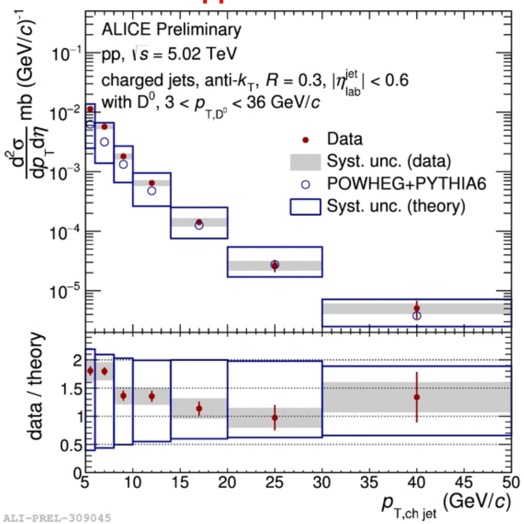


PYTHIA8: JHEP 05 (2006) 026
DIPSY: JHEP 1503 (2015) 148
HERWIG7: EPJ C76 (2016) no.4 196

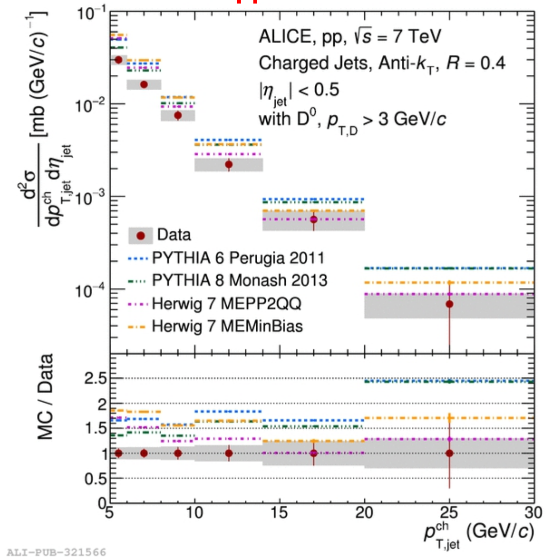
- Ξ_c^0/D^0 as well as Λ_c^+/D^0 are underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889
- Detailed measurements of charm baryons provide valuable input for theoretical understanding of HF fragmentation

Charm production: D^0-jet cross sections

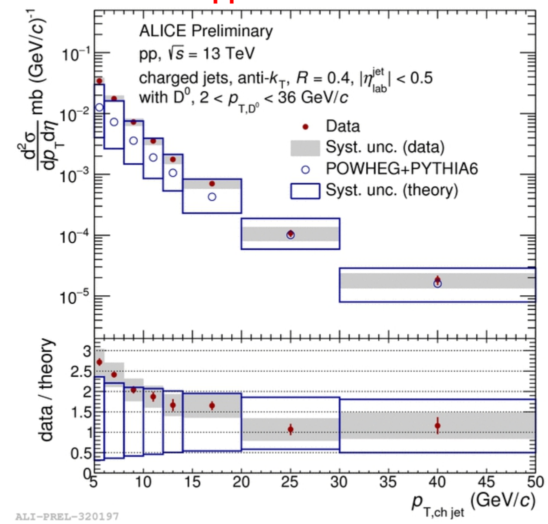
pp $\sqrt{s}$=5.02 TeV



pp $\sqrt{s}$=7 TeV

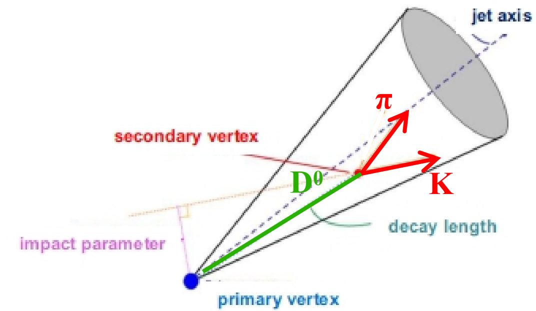


pp $\sqrt{s}$=13 TeV



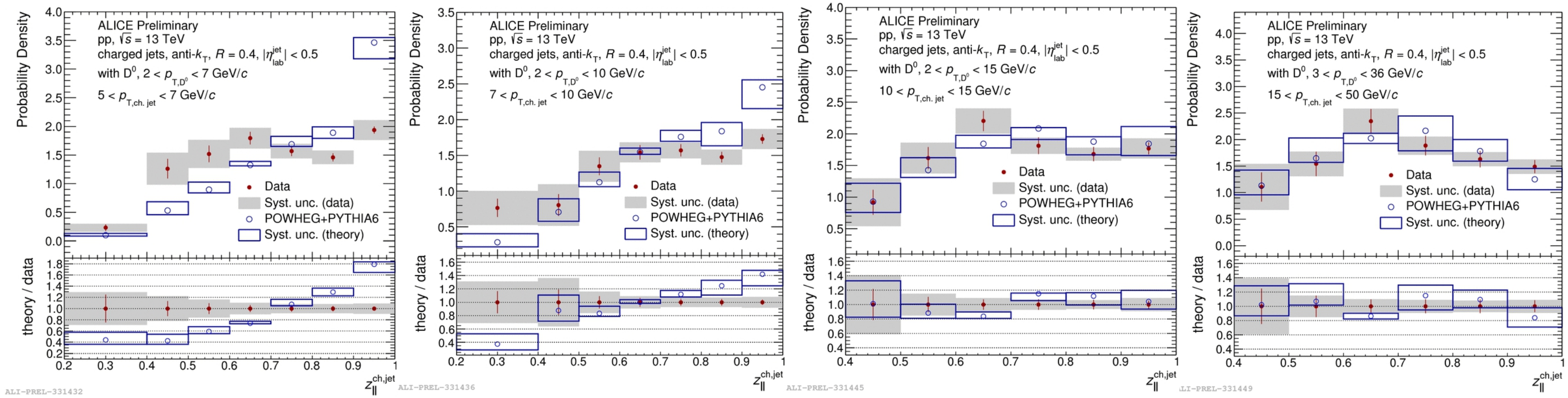
JHEP 1908 (2019) 133

- Analysis technique
  - Identify D^0 mesons via hadronic decays
  - Replace decay products with D^0 in jet
- Comparison with models
  - NLO POWHEG+PYTHIA (hvq) calculations consistent with data (only marginally at low-p_T)
  - Neither LO PYTHIA 6 and 8, nor NLO HERWIG 7 describe the cross-section



Charm fragmentation: D-jet $z_{||}$ vs. p_T

5<$p_T^{ch,jet}$<7 GeV/*c* **7<$p_T^{ch,jet}$<10 GeV/*c*** **10<$p_T^{ch,jet}$<15 GeV/*c*** **15<$p_T^{ch,jet}$<50 GeV/*c***



pp √*s*=13 TeV

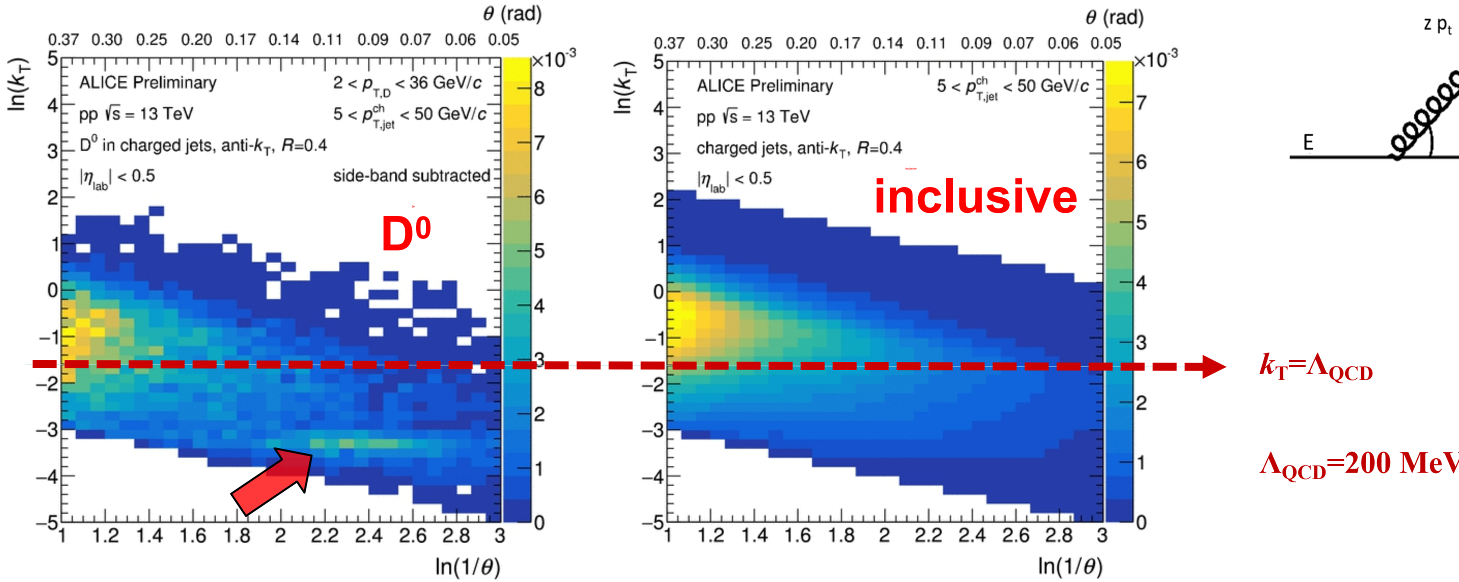
- **parallel momentum fraction**
  - Characteristic to heavy-flavor fragmentation

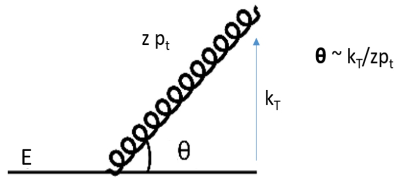
$$z_{||}^{ch} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

- D-meson fragmentation is softer at high p_T than at lower p_T
- POWHEG+PYTHIA6 predicts a stronger change towards low p_T

Dead cone: the Lund plane

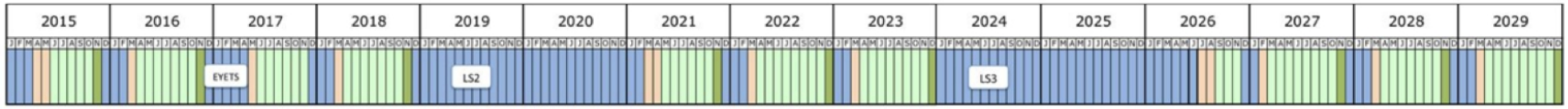
- D^0 as well as inclusive jets: Reclustering with C/A
  L. Cunqueiro, M. Ploskon, PRD 99, 074027
- Lund plane populated with all splittings of the radiator's prong
  - D^0: depletion expected at low angles (~higher $\ln(1/\theta)$ values)
    Note: 10 to 15% feed-down contribution in D^0 from b





- k_T-cut to remove contamination from hadronization, decay and the underlying event

ALICE Upgrade for Run-3 and Run-4



Run 2: $\mathcal{L}_{Pb-Pb} = 1.0\ nb^{-1}$

Run 3: $\mathcal{L}_{Pb-Pb} = 6.0\ nb^{-1}$

Run 4: $\mathcal{L}_{Pb-Pb} = 7.0\ nb^{-1}$

Shutdown/Technical stop
Protons physics
Commissioning
Ions

- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb^{-1} (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout